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THE PHYSIOPATHOLOGICAL EFFECTS OF ACCELERATION ON ASTRONAUTS

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16. Abstract

The physiopathological effects of types of acceleration varying in direction of application, intensity, and duration are discussed. Reasons are given for the selection of a take-off position allowing the astronaut to receive the accelerative force transversally. Studies of the oxygen saturation level of the arterial blood are reviewed with attention to the influence of this factor on the psychomotor response capability of the individual. Cardiorespiratory problems, including pulmonary collapse, are given particular attention, and there is some discussion of changes in cell morphology and the problem of weight loss due to dehydration.

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THE PHYSIOPATHOLOGICAL EFFECTS OF ACCELERATION ON ASTRONAUTS

L. Tabusse and P.M. Pingannaud

Astronauts have now existed for six years. Their first steps in space have led to the threshold of a tremendous new adventure. However before the next stages are accomplished, taking men to the moon and probably on to other planets, one cannot help but wonder about the physiological stresses which must be tolerated by astronauts in order to overcome gravity and return safely to their natural milieu. In spite of recent accidents, it should be recognized that up to now, the conditions during propulsion, orbital flight, and re-entry have never exceeded the limits of human tolerance. However, it remains to be seen whether the experience which has been gained will be sufficient to provide an estimation of the medical problems which may occur in the future conquest of space. Is there sufficient perspective at present to evaluate the long-term effects of detrimental factors which must be tolerated during flight? /11*

Some information, and an adequate basis on which to evaluate the future, seems to be provided by one specialized but highly important and fundamental field. This is the field of acceleration. This phenomenon occurs primarily during launching and during the recovery phase of the satellites, and the problems presented in this area are not very different from those encountered in aeronautics. Consequently this field has been the subject of a large number of studies and considerable speculation.

Acceleration is thus of prime importance in aerospace medicine: an approach to this subject reveals the degree to which man's conquest of his environment is in actuality a step-by-step process

*Numbers in the margin indicate pagination in the foreign text.

requiring the most rigorous experimental safeguards.

Before examining certain aspects of the problem of the effects of acceleration on astronauts, the terminology generally used in this area by physiologists should be pinpointed. The effects of acceleration depend as much on the direction in which the force is applied on the organism as on the intensity and duration of the phenomenon. If in addition one notes that the effects of acceleration depend more on the direction of the forces of inertia than on the direction of the acceleration itself, it becomes evident that unless some care is used, a certain amount of confusion may ensue and detract from comprehension of the observed phenomena. This is why a certain linguistic consistency has been obtained in /12 response to various requests: thus abandoning the letter "g" used by physicists, physiologists generally designate the acceleration corresponding to the acceleration of gravity (9.81 m/s^2) by the letter "G".

Furthermore, the direction of acceleration is denoted by the direction of the effects of acceleration. For example, the effects of acceleration on a subject who is standing in a vertical position and who is propelled forward will be felt transversally in an anterior-posterior direction, from the stomach to the back. If the subject were propelled to the rear the direction of this transverse acceleration would thus be reversed, that is, posterior-anterior, or again, from back to stomach. Thus for each spatial plane acceleration may occur in a given direction or in the exact opposite direction. Finally, a system of reference has been adopted consisting of x, y, and z coordinates, the three spatial dimensions in relation to the axis of the body.

In addition the acceleration is modified by a + or - sign depending on its direction of application in a given plane. The following general relationships result:

Transverse anterior-posterior, front to back	+Gx
Transverse posterior-anterior, back to front	-Gx
Transverse from the left side	+Gy
Transverse from the right side	-Gy
Head-to-couch position	+Gz
Couch-to-head, negative	-Gz

These terms have provided a clear means of approach to the problem of the physiopathologic effects of acceleration. The acceleration may, of course, vary in duration, intensity, and speed of occurrence. Since each of these physical parameters may develop independently of the others, particularly complex phenomena may be expected. Nevertheless the types of acceleration experienced by aviators and astronauts can be classified schematically.

1. Short-Term Acceleration

Effective for less than one second.

This type of acceleration is of no physiopathological interest unless it is of high intensity or is repeated. It is encountered during ejection, for example, during the sudden decelerations occurring in crashes, or during fighting maneuvers.

2. Long-Term Acceleration

One of the most apparent effects of this type is hemodynamic retention. The principal example of this type of acceleration is that produced by aircraft maneuvers and during propulsion of satellites. The human tolerance is a function of the three basic physical parameters: intensity, duration, and direction of application.

Effects of Longitudinal Acceleration, +Gz and -Gz

The effects of long-term longitudinal acceleration (+Gz and -Gz) as a function of intensity.

+Gz: at 1-2 G -- subject flattened in couch
3 G -- motor capability greatly reduced
4 G -- narrowing of field of visions and grayout
5 G -- blackout
6 G -- loss of consciousness

-Gz: at 2 G -- congestion of the cephalic extremity with headache
3 G -- intracranial hypertension and incipient hemorrhage
4 G -- redout, maximum tolerable

Aside from immobilization caused by the increase in apparent weight under the effects of $\pm$Gz acceleration, the overall effects felt by the subject being accelerated are due to the mobilization of the entire blood mass under the effects of inertia, accumulating at the feet when the subject is propelled upward and being forced into the upper end of the body when the propulsion is downward. Thus hematic effects predominate in this type of acceleration, which develops along an axisoparallel to the axis of the body. Its immediate repercussions on the functional capabilities of the primary organs (heart and brain) quickly limit the tolerance of the individual.

Effects of Transverse Acceleration (+Gx and -Gx)

In this case the hemodynamic effects are of little importance. Von Diringshofen (1932), followed by a number of other investigators, has satisfactorily demonstrated that the tolerance level is much higher here. Primarily involved are mechanical factors which affect any parts which can be depressed or moved in a transverse direction. Thus during high intensity acceleration the thoracic cage is virtually crushed. On the other hand, when moderate this type of acceleration can be tolerated relatively well:

Tolerance of transverse acceleration as a function of time and intensity:

2 G: 24 hrs
8 G: 1 hr 40 min
12 G: 30 sec
15 G: 10 sec

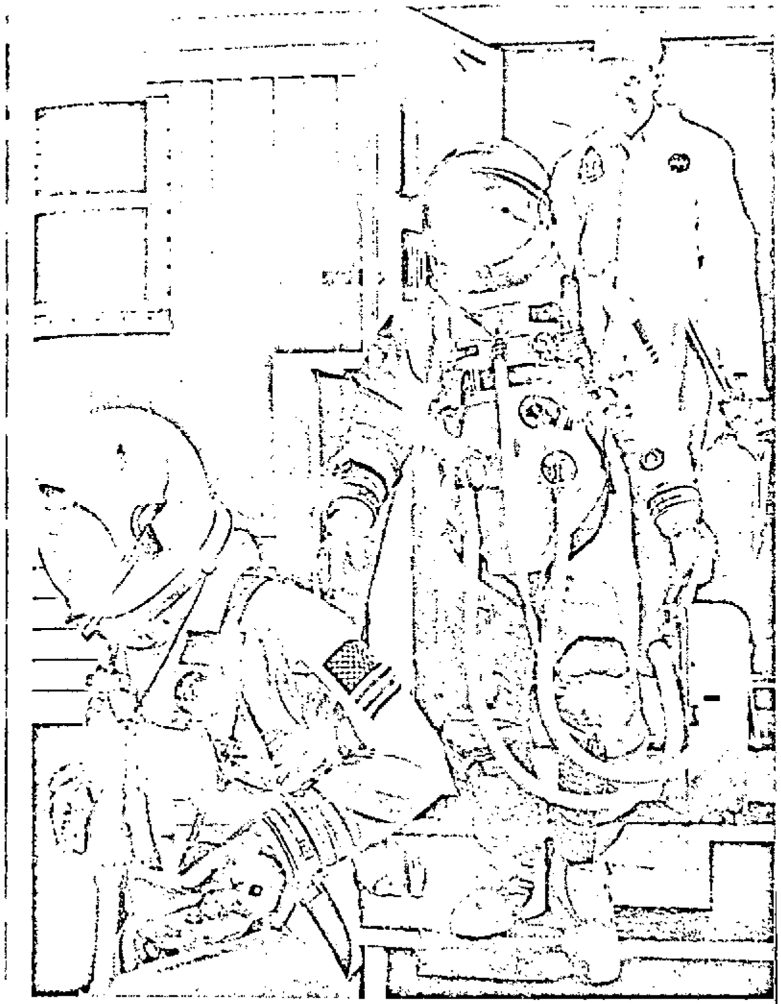
A mere glance at this general pattern shows why space program /13 officials have decided to solve the acceleration problem by placing the subjects in such a way that they experience virtually only transverse acceleration. Thus any approach to the problem of the effects of acceleration on astronauts from a biological angle must begin with the physiological effects of transverse acceleration. The experience which has been acquired in this area has considerably advanced our knowledge.

To furnish a frame of reference we should note the types of acceleration to which astronauts are subjected.

Types of Acceleration Experienced by Astronauts

Acceleration occurs primarily in two phases of flight: propulsion and re-entry.

1) During launching: the speed which must be attained to thrust the capsule into orbit is 8,000 m/sec. This speed may be reached more or less rapidly depending on the modifications which



Charles Conrad and Richard Gordon make their way to the launch area (U.S.I.S. photo).

can be made in the duration and intensity of acceleration. Current technological requirements limit the theoretical possibilities.

Maintaining the acceleration within tolerable limits while simultaneously prolonging it until orbital speed is attained has been possible only by separating successive stages of the spacecraft. Furthermore, this compromise was not satisfactorily reached until the crew were placed in reclining positions enabling them to tolerate 7 to 8 g. In this way the spacecraft is able to pass through the dense atmospheric layers quickly, proportionately

Armstrong and Scott in the Gemini 8 capsule (U.S.I.S. photo).

reducing the amount of energy expended in propulsion. To escape the earth's gravitational field and to reach escape velocity a speed of 11,000 m/sec must be attained. An amplification of the present problem can therefore be expected in the near future when the first moon launches are made. The nature of the problems involved, however, remains the same, and although it is advantageous from a physical standpoint to reduce the intensity of acceleration, a compromise will still certainly be necessary: the slower the rate of acceleration, the more this phase must be prolonged in order to reach the desired speed.

Thus, although two minutes of acceleration at 6.65 g is sufficient to reach orbital speed, ten minutes would be necessary if the acceleration were reduced to 1.39 g.

On re-entry, the problem is presented in appreciably similar terms.

The technique for satellite recovery is also limited by two main factors:

-- human tolerance of deceleration,
-- and aerodynamic heating.

In effect, even if one considers that with suitable protection and placement man will be able to tolerate deceleration at more than 10 g, there is danger that the heat generated at this rate of deceleration would set the capsule on fire.

Finally, the dense layers of the atmosphere must be entered at a low angle and the deceleration should not exceed 8 to 9 g. There has been advances in this area, and electronic monitoring of re-entry arcs has so far permitted deceleration at a maximum of 5 G. For the future the problem has no practical solution as yet, but experts have already determined the principles for recovery. According to these data it appears that the return of lunar or interplanetary spacecraft would present much more delicate problems than those of a capsule following a low orbit:

-- After the spacecraft has been brought from its lunar orbit into a highly eccentric terrestrial orbit, braking, accomplished by igniting the retrorockets, must occur at the apoggee in order to be effective; but subsequent events depend on the braking speed. In orbits with a distant apogee the speed of the spacecraft approaches 11 km/sec. Consequently braking must be extremely gradual once the vessel has entered the dense layers of the earth's atmosphere. For future astronauts, therefore, physiologists project decelerations of moderate intensity on the order of 3 to 4 G, but of relatively long duration. Nevertheless it should be noted that a minimal error in calculating the trajectory may lead to /14
much faster deceleration, since the density of the atmosphere doubles every five kilometers. Consequently a re-enetry designed to occur at a deceleration of 4 G at an altitude of 60 km may be

converted at only 55 km into violent braking with a deceleration of 8 G.

However, ignoring possible failures in the monitoring devices, moderate long-term accelerations can be expected in the future during re-entry as well as during the active propulsion phases. Other types of acceleration may occur, but only occasionally and as a result of accidental factors: poor stabilization of the capsule resulting in radial acceleration and rotation, or an exaggerated landing speed during a lunar landing, for example, causing sudden deceleration. Finally, during prolonged flights the crews may undergo acceleration in a small-diameter centrifuge to prevent any harmful gravitational effects on the cardiovascular system. But this would not involve acceleration capable of producing physiopathological effects. This is why, in the final analysis, the primary physiological and medical concern continues to be transverse acceleration, as we have noted, especially when the acceleration occurs over long periods of time or is repeated, since this will be the type of phenomenon to which astronauts will be exposed.

How far has knowledge advanced in this area? First there might be some value in recalling how the problem of the position of the astronaut during acceleration was solved. The position assuring maximum tolerance was selected and adopted as the result of a long experimental study which was analyzed and described in this journal by Grandpierre and Violette in 1963.

Given the reasons for selecting a transverse position to eliminate the hemodynamic effects of acceleration, one might wonder why a 90° angle was not adopted to obtain maximum tolerance. The answer is that during practical tests under these conditions the subjects experienced intolerable pain in the sternal and epigastric regions at 8 to 12 G. This was accompanied by various cardiac difficulties and respiratory failure. Experience has shown that in practice the best conditions occur when the vector representing the summation frequency of acceleration makes an angle of about 80° with the long axis of the body.

During both launch and re-entry the trunk is therefore inclined at an angle of 15-20° from the horizontal, the legs flexed, and the astronaut is pressed tightly into the contoured couch, his body conforming to its shape. In this position he is able to withstand acceleration without apparent injury. To evaluate future prospects, however, it appeared necessary to go beyond the general physiological study whose initial goal was only to determine the limits of human tolerance. But investigators were hindered in this attempt by the relative imprecision of the medical criteria: "tolerable" pain, "adequate" respiration, continued alertness. However, since it has been proven that the principal organic functions are maintained during the take-off of the carrier rocket and the return of the space capsule, data from more thorough biological analysis should now be taken into account. This new stage of research in aerospace medicine may be compared to pharmacological situations where after a drug has been demonstrated effective against a given disease, it must then be proven at least relatively harmless and the extent of any secondary effects which may be incurred by its usage must be measured.

Physicians and biologists have not awaited the success of the space efforts to turn their attention to these problems. A few main ideas can be gathered from the large number of studies which have already been performed:

An initial point of interest naturally consists in psychomotor performance during the phases of acceleration. Kaehler and Meehan of Wright-Patterson have conducted experiments on human subjects in this area, using the classical light signal test. The

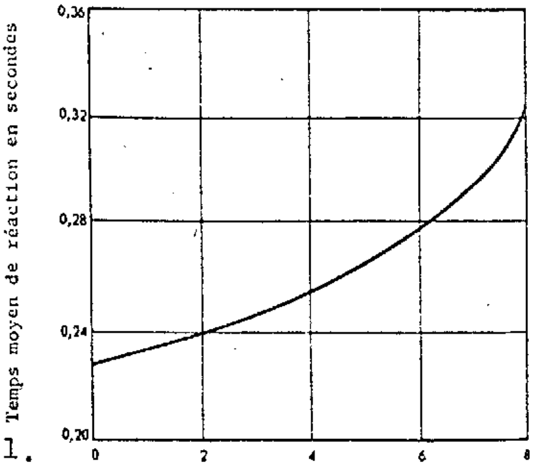


Fig. 1. +Gx acceleration (after Kaehler and Meehan). Influence of transverse acceleration on time of response to light stimuli.

Key: 1. Average response time in seconds.

response time required for the performance of simple manual tasks was recorded for accelerations of increasing intensity (Fig. 1).

This response time was increased by about 0.1 sec. in shifting from 1 to 8 g. Prolongation of the psychomotor response time was still more appreciable for more complex tasks.

Some data in this area /15
have also been accumulated in France during the experimental research which preceded launching of the Vesta biological capsules containing the macaques "Martine" and "Pierrette." Head Physician Chatelier conducted this research at the Teaching and Research Center for Aeronautical Medicine. The monkeys were placed in a centrifuge where propulsion phase acceleration was reproduced, that is, acceleration of 9.5 to 10 G for 58 sec. During the first tests the animal's appearance and gestures evidenced some disorientation. After three or four tests, however, it appeared to be completely adapted. Furthermore, during practical experiments conducted on March 7 and 13, 1967, at the Hammaguir launching field, psychomotor performance was obtained at up to 7 G. This stress phase apparently did not change the conditioned reflexes of the animal in any way; throughout zero gravity flight it continued to respond successfully to stimuli. The behavior of subjects undergoing acceleration primarily depends on the manner in which the nerve centers are supplied with blood and oxygen. Consequently a large number of studies have been oriented toward this problem. Precise data have been obtained, primarily

by the NASA Space Center in Houston. The oxygen saturation of the arterial blood is measured by means of a calibrated oxymeter placed in the ear of the subject, who undergoes a system of accelerations reproducing actual acceleration. The gaseous environment is either the ambient air or pure oxygen at 5 PSI (1/2 atmosphere), which corresponds to the atmosphere in American space capsules. The results obtained have incontestably demonstrated a gradual desaturation of the arterial blood as a function of the intensity of acceleration. However, if one analyzes the results obtained with different tyeps of acceleration continued for two-minute periods (Fig. 2), or those obtained with acceleration similar to that occurring during re-entry (Fig. 3), one finds that the O_2 saturation always remains higher than 80%. This is an important fact. In effect, although there begins to be appreciable discomfort at 90% of saturation, the normal level being between 97 and 100%, this is still some distance from the 65% figure which represents the threshold of anoxemic syncope. Consequently, although the astronaut is safe from large-scale movements of the blood mass and thus from ischemic anoxia due to an insufficient supply of blood to the brain, he is nevertheless exposed to a certain degree of hypoxemia. The reasons for this phenomenon have been the subject of research on the cardiorespiratory system. The tolerance for transverse acceleration is apparently limited by the incapacity of the heart and the lungs to supply adequately oxygenated blood to the tissues.

It was possible to determine the mechanisms of this deficiency in the lungs by the combined use of various methods of investigation. Measurement of the respiratory frequency and the volume of air displaced had shown that despite an acceleration in the respiratory rhythm and an increase in the ventilatory flow per minute, there was a drop in arterial blood oxygen saturation in virtually all the subjects who underwent acceleration. Radiographic and cinematoradiographic methods supplied the reason for this change in the respiratory function by revealing the extensive morphological changes produced in the pulmonary region by acceleration. Thus Sandler observed a compression of the anterior-posterior axis of the thorax which was proportionate to increases in acceleration, and was accompanied by compression of the dorsal segments of /16 the lungs. Part of the functional area of the lungs is thus effectively cut off. The result is a decrease in the ventilation/perfusion ratio. Arterial-venous shunts are produced. Mixed venous blood, short-circuiting the pulmonary capillaries, combines with the oxygenated blood and, contaminating it, decreases its saturation.

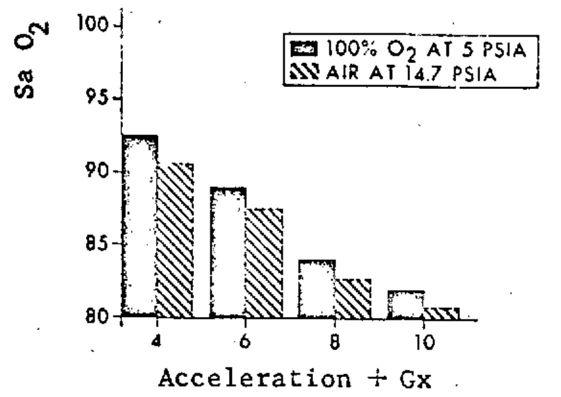


Fig. 2. Saturations obtained after two minutes of transverse acceleration, after Alexander.

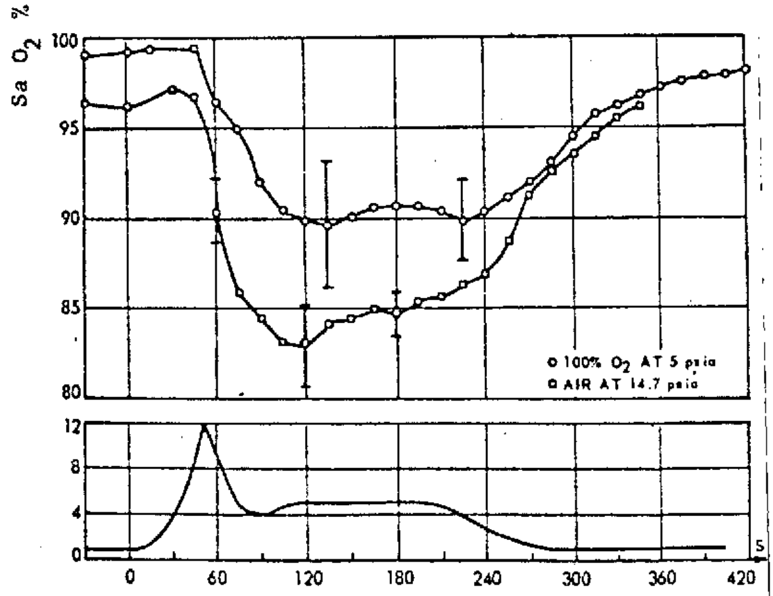


Fig. 3. Influence of transverse acceleration on the oxygen saturation of the arterial blood, after Alexander.

Added to these problems are difficulties in the ventilation mechanism itself, both in the thorax and in the diaphragmatic cupula, whose upper part is forced upwards, as has been shown by cinematoradiographic studies. The cardiac mass is appreciably shifted and pushed in a posterior direction. A. Brooks, D.E. Torphy and S.D. Leverett have assembled electrocardiograms from selected subjects who underwent +Gz and +Gx acceleration. They were surprised to find a high incidence of arrhythmia, especially during transverse acceleration. Finally, two pathogenic factors were presented in relation to the respiratory function: on the one hand, atelectatic phenomena, that is, compression of a given area of the lungs, were found to be causative factors resulting in a virtual functional "amputation." On the other hand, there was a possibility of pulmonary collapse caused by the respiration of pure oxygen. The oxygen, which can be completely resorbed, quickly diffuses through the alveolocapillary membrane. Consequently when there is no nitrogen to be resorbed, the alveolus collapses.

With reference to the heart, the arrhythmic phenomena would be related to hypertension produced in the right auricle.

Precordialgic pain accompanied these displacements and these changes in the cardiorespiratory function. The problem thus becomes to determine whether the mechanical effects observed are an adequate explanation for the pain, or whether the latter should be attributed to a reduction in coronary flow of the type observed in angina pectoralis. Other theories have also been offered, such as movement of the xiphoid process or the occurrence of relative hypertension in the lesser circulation. Research is in progress and no definitive answer has been supplied so far.

In any case, these varied factors have made the respiratory function the center of attention for research. In the opinion of some investigators, study of this function will provide a means of determining the limits of human tolerance to transverse acceleration. Although the tolerance for +Gz acceleration can be determined fairly accurately because of the occurrence of blackouts, the tolerance for transverse acceleration is much less precisely known. Currently these tolerance limits are subjective and depend to a great extent on the motivation of the subjects and their ability to withstand pain and discomfort. The oxygen saturation of the arterial blood would therefore seem to constitute a valuable physiological reference point. For this reason some laboratories are studying the correlation between the SaO_2 and the ability to perform predetermined stasks.

The application of histologic techniques to study of the physiopathological consequences of acceleration hase provided an extremely valuable complement to knowledge in this area. Studies performed at the histology laboratory of the First Medical College in Moscow have been broadly disseminated in recent conferences on aerospace medicine. Eliseyev, in particular, has reported on research performed on an entire series of animal species: monkeys, rats, dogs. Most of the organs of these animals were examined under the microscope after they had been exposed once or repeatedly to transverse accelerations at 8 to 12 g. The blood vessels supplying the dorsal parts of the organism were the sites of more or less marked alterations. Histochemical changes indicative of metabolic disturbances were observed in the large vessels of the pulmonary region. The length of time for which the animals were exposed to acceleration appeared to be of prime importance. In addition, repeating the acceleration appeared to result in much more moderate reactions. Under these conditions the authors observed hypertrophy of the vascular walls and a much lower incidence of hemorrhage. They are thus of the opinion that a rational training method may be sufficient to improve man's tolerance of acceleration. On a pathogenic level, Eliseyev believes that hypoxia due to the hemodynamic changes lies at the basis of the dystrophic or degenerative reactions observed at the cell level.

Microscopic techniques have made it possible to recognize changes in cell structure after acceleration; these changes primarily affect the nucleus and the mitochondria, which play a highly important role in the functioning of the cell.

The problem of repeated positive (+Gz) accelerations of low intensity and long duration has already been under concentrated study in France for some time. In 1959, Senelar, Loubière and Violette studied anatomical lesions resulting from this type of acceleration. The cumulative effects were analyzed and attention was quickly focused on the kidney due to the early appearance of hematuria. It was possible to reveal the development of a physio- /17
pathological process in this organ occurring in three phases: after a period of tolerance with a possible regression of symptoms, definite lesions appeared in the renal tissue. These lesions were capable of developing on their own even after the stress was removed. Under the experimental conditions mere venous congestion could thus become actual nephritis. More recently, Loubière et al. have revealed and analyzed cell changes in the suprarenal glands, whose reactivity to stress is well known; these changes were probably attendant on congestion and hypoxia. Judging from the nature of the lesions observed it would seem that tension in the neuroendocrine system is one result of acceleration. In Poland, P. Czerski et al. have made analogous observations in relation to rats subjected to 3 G of acceleration daily for 20 days.

Even acknowledging that the intensity and duration of acceleration in these studies makes the experimental conditions much more rigorous than the actual conditions during space flight, one must still attach the greatest possible value to data obtained in this way.

This cautious position is all the more advisable since other harmful effects induced by space flight may decrease the tolerance for acceleration.

Among these effects special importance must be given to dehydration, which is known to be an important preoccupation of both Soviet and American researche

All the astronauts experienced weight loss during their orbital missions:

Glen	3.1% of total weight, that is	156 g/hr of flight
Carpenter	3.9%	180
Schirra	3.1%	132
Cooper	5.3%	102

For the most part this weight deficit was due to water loss. A large number of studies have suggested that a certain degree of dehydration could be harmful.

From an experimental standpoint, investigators such as Greenleaf et al. have observed a decrease in the tolerance for centrifugally produced positive acceleration (+Gz) after a weight loss of 4%. On the other hand, Ladell has established that the body may become dehydrated and lose 5% of its weight before any changes occur. In the final analysis, however, the flights have been of fairly short duration, so far, and it is advisable to avoid any preconceptions as to what the future may hold in store.

Ambitious projects are planned for the next few decades: NASA's Marshall Space Flight Center has set up the following program:

1975: flight close to Venus with a crew of three astronauts,
1979: same mission to Mars,
1980-1981: landing on Mars with a crew of eight or nine astronauts.

To complete these projects successfully it will obviously be necessary for the crews to maintain perfect medical-physiological condition after undergoing the numerous stresses incurred during flight. Is this likely to be the case, judging only on the basis of research on the acceleration phase? At this point the question is still problematic.

Conclusion

In order to travel in space man must endure numerous physiological stresses. Acceleration is one of the most potentially harmful of these factors. Before the space age, however, aviators were already learning to tolerate and protect themselves from this type of stress. Thus aerospace medicine is only an extension of aeronautical medicine, and the bases are already well established on which man will find the means to adapt himself and to reach the tremendous speeds necessary to attain orbit without any apparent damage to his system. This specific problem has not yet been solved, however, even though appearances may indicate to the contrary: the large amount of research devoted to the subject reveals that a great many unknowns still exist.

The use of modern techniques of biological investigation has made it possible gradually to reveal the physiopathological mechanisms, functional changes and even cell lesions which may be induced by acceleration under predetermined conditions. An analysis of the overall data provided leads to cautious optimism toward the future.

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